Year: 2003

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DOI: https://doi.org/10.1117/12.510449

Originally published at:
Kneubühler, Mathias; Schaepman, Michael E; Thome, Kurtis J; Schläpfer, Daniel R (2003). MERIS/ENVISAT vicarious calibration over land. In: Sensors, Systems, and Next-Generation Satellites VII, Barcelona, Spain, 8 September 2003. SPIE - International Society for Optical Engineering, 614-623.
DOI: https://doi.org/10.1117/12.510449

MERIS / ENVISAT Vicarious Calibration Over Land

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ABSTRACT

The launch of ESA's ENVISAT in March 2002 was followed by a commissioning phase for all ENVISAT instruments to verify the performance of ENVISAT instruments and recommend possible adjustments of the calibration or the product algorithms before the data was widely distributed. The focus of this paper is on the vicarious calibration of the Medium Resolution Imaging Spectrometer (MERIS) radiance product (Level 1b) over land. From August to October 2002, several vicarious calibration (VC) experiments for MERIS were performed by the Optical Sciences Center, University of Arizona, and the Remote Sensing Laboratories, University of Zürich. The purpose of these activities was the acquisition of in-situ measurements of surface and atmospheric conditions over a bright, uniform land target, preferably during the time of MERIS data acquisition. The experiment was performed on a dedicated desert site (Railroad Valley Playa, Nevada, USA), which has previously been used to calibrate most relevant satellite instruments (e.g., MODIS, ETM+, etc.). In-situ data were then used to compute top-of-atmosphere (TOA) radiances which were compared to the MERIS TOA radiances (Level 1b full resolution product) to determine the in-flight radiometric response of the on-orbit sensor. The absolute uncertainties of the vicarious calibration experiment are found between 3.36-7.15%, depending on the accuracies of the available ground truth data. Based on the uncertainties of the vicarious calibration method and the calibration accuracies of MERIS, no recommendation to update the MERIS calibration is given.

Keywords: ENVISAT, MERIS, Multitemporal Vicarious Calibration, Calibration Accuracy, Railroad Valley Playa

1. INTRODUCTION

1.1 MERIS

The Medium Resolution Imaging Spectrometer (MERIS) [1] is one of ten instruments on board ESA's ENVISAT platform. MERIS is a 68.5° field-of-view pushbroom imaging spectrometer that measures the solar radiation reflected by the Earth, at a ground spatial resolution of 300 m (full resolution) and 1200 m (reduced resolution), in 15 spectral bands in the visible and near infra-red. MERIS allows global coverage of the Earth in 3 days. MERIS data products provided by ESA include georeferenced TOA radiance data (Level 1b) as well as various water, land and cloud products (Level 2).

Full resolution data sets of the Railroad Valley Playa test site (TOA radiances, Level 1b) from four different days between August and October 2002 are investigated. Multitemporal vicarious calibration allows both for monitoring sensor stability and for investigation of the robustness of the vicarious calibration method.

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1.2 Railroad Valley Playa Test Site

The dry lakebed of Railroad Valley Playa, Nevada is located at 1.35 km above sea level (38.504° N latitude, 115.692° W longitude). It is a desert site with no vegetation. Temporal records for this site show reflectance variations as a function of time of year, with lowest reflectance in the winter months due to a rising water table. The accuracy of vicarious calibration experiments over land is highly dependent on the choice of an appropriate calibration target. Ideally, such a calibration site should be flat, bright, spatially uniform, spectrally stable over time, near lambertian for small angles off nadir, and of sufficiently large spatial extent. Desert playas are preferred for vicarious calibration of moderate spatial resolution sensors due to their optical properties, predictably sunny conditions and low atmospheric aerosol loading [2].

1.3 Vicarious Calibration

Vicarious calibration is an independent pathway for monitoring instrument radiometric performance, including error assessment with reflectance standards, field instruments and atmospheric radiation measurements. In general, the experiment follows a reflectance-based approach with ground measurements of the atmospheric optical depth and surface reflectance over a bright natural target [3].

In this experiment, in-situ sunphotometer data from all four dates of MERIS data takes were available. However, extensive wildfires in California and Oregon led to spatially very varying atmospheric conditions. As a consequence, large variations in the atmospheric optical depth must be assumed within small regional extent, depending on whether clouds of smoke were in the line of sight of both the sun photometer or MERIS. Thus, only the sun photometer data of August 22, 2002 could be used to determine aerosol model and horizontal visibility, subsequently applied for radiative transfer calculation. For the other three dates, large offsets between measured and modelled TOA radiances indicate an inadequate atmospheric characterization. In these cases, a best fitting atmosphere was applied for vicarious calibration, without the use of any sun photometer data. MODTRAN-4 [4][5], a radiative transfer code (RTC) is used, constrained by field data, to calculate the top-of-atmosphere radiance at the sensor. Input parameters include ground measurements of the surface reflectance, sun-target-sensor geometries and atmospheric properties (aerosol model, horizontal visibility).

2. EXPERIMENT DATA ACQUISITION

2.1 MERIS Data

Between August and October 2002, five potential full resolution data sets of MERIS were acquired over Railroad Valley Playa. The data sets of August 12, August 22, August 31 and October 21 are used for vicarious calibration (see Table 1). A data set of September 9 could not be used because of cloud cover.

Acquisition Date (2002)	Acquisition Time (UTC)	Absolute Orbit	Relative Orbit	Sun Zenith [°]	Sun Azimuth [°]	Sensor Zenith [°] (off nadir)
August 12	18:17	2357	299	31.68	132.75	12.06
August 22	18:02	2500	442	35.16	131.36	12.23
August 31	18:20	2629	70	36.27	141.95	16.98
October 21	18:17	3359	299	52.36	157.73	12.06

Table 1: MERIS Full Resolution data sets (Level 1b) used for vicarious calibration.

MERIS full resolution subsets of Railroad Valley Playa (Nevada) from the four dates under investigation are given in Figure 1. The symbol identifies the VC test site.

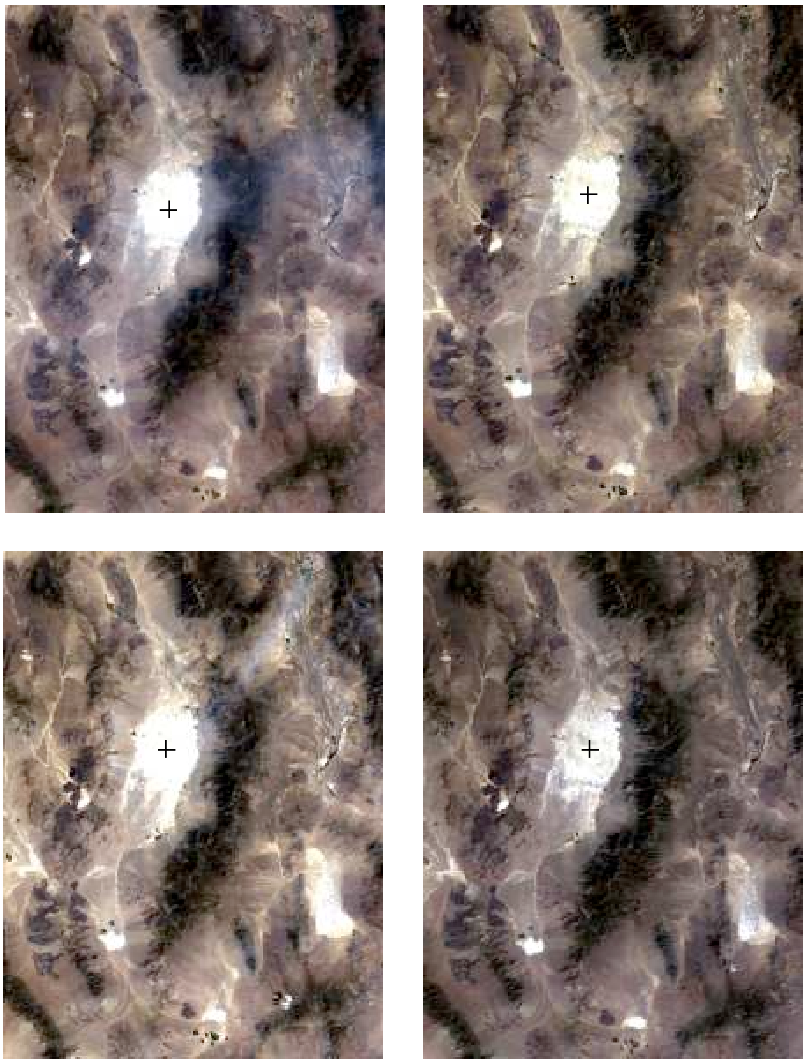

Figure 1: MERIS Full Resolution subsets of the Railroad Valley Playa test site.
Top: left: August 12, 2002, right: August 22, 2002,
bottom: left: August 31, 2002, right: October 21, 2002.

2.2 In-Situ Field Measurements

Field data acquisition activities aimed at characterizing (a) the spectral reflectance of the bright surface and, (b) the atmospheric path from the sun to the surface. Therefore, the following ground field instruments were operated in the field:

An Analytical Spectral Devices, Inc. (ASD) Portable Spectrometer to measure the surface spectral hemispherical directional reflectance factor (HDRF) (only in the nadir view direction) as a function of wavelength in the spectral range between 350 nm and 2500 nm. The variability in the spectral measurements, due to target inhomogeneity and instrument calibration uncertainties is around ±3% over the 350-1200 nm range (±1 stdev from the mean). For the August 22, 2002 MERIS overflight, spectral ground truth data was acquired on the same day. For the August 12, August 31 and October 21 data takes, spectral ground truth data closest to these dates were used for vicarious calibration. As the spectral behaviour of the playa is mainly driven by moisture, only minor variations in reflectance are present over time, if no rainfall occurred. Table 2 lists the spectral ground truth data used for vicarious calibration. As can be seen in Figure 2, reflectance differences between summer and autumn ground truth data exist, due to intermediate rainfall.

MERIS acquisition date	Spectral ground truth acquisition date
August 12, 2002	August 15, 2002
August 22, 2002	August 22, 2002
August 31, 2002	August 22, 2002
October 21, 2002	September 21, 2002

Table 2: MERIS acquisition dates and corresponding spectral ground truth used for VC.

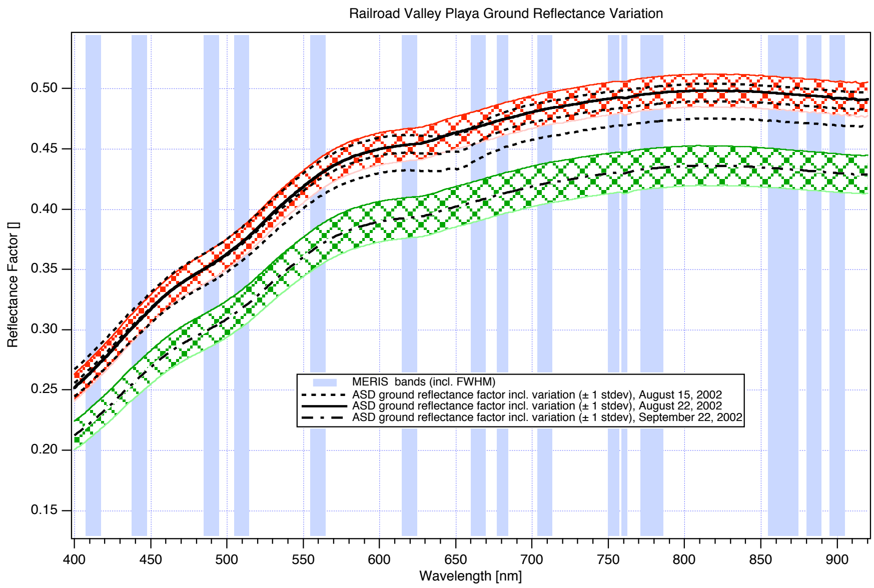

Figure 2: Spectral ground truth data of Railroad Valley Playa used for VC.

A CIMEL sun photometer to measure the total atmospheric optical depth τ. Langley analysis is used to retrieve the aerosol optical depth from these measurements in seven spectral channels in the 400-900 nm range. This instrument makes part of the AERONET network. Sun photometer data was only used for atmospheric characterization on August 22. For the other three investigated dates of MERIS vicarious calibration, large regional variations due to clouds of smoke from wildfires did not allow for a reliable characterization of aerosol model and horizontal visibility from sun photometer data.

3. ANALYSIS AND RESULTS

3.1 Radiative Transfer Calculation of TOA Radiance

In a first step, the definition of an appropriate atmosphere, as it was present on the various dates of data take, must be addressed. An analytical approach of deriving atmospheric key parameters from in-situ sun photometer data and radiative transfer code inversion is first applied to all four dates of vicarious calibration. The reference solar irradiance of Thuillier [6], as adopted for ENVISAT by ESA, is used for the atmospheric modelling. The use of MODTRAN standard irradiance data would result in mean deviations of around 4.5% for the radiance calculation over the 400-900 nm wavelength range. Test site location, data acquisition times and dates, as well as the sun-target-sensor geometries are optimized for the specific ground truth area (9 pixels) in the MERIS data sets.

A reasonably low relative rms error (5.943%) for the best fit between MERIS measured and modelled TOA radiances based on sun photometer data inversion could only be achieved for the August 22, 2002 data. The best fitting atmosphere

consists of an urban aerosol model and a horizontal visibility of 40 km (see Figure 5). An urban aerosol model accounts best for the unusually high aerosol loading, especially black carbon [7], due to the wildfires. Concerning the three other dates, relative rms errors between 10-20% are observed. Large offsets between measured and modelled TOA radiances are found, indicating an unsufficient characterization of the present atmosphere using the sun photometer data. The heterogeneity of the smoke clouds, in combination with the particular sun-target and sensor-target geometries could be possible reasons.
As a consequence, a second approach for vicarious calibration of the multitemporal data set is performed, without the use of any sun photometer data. MERIS measured TOA radiances are compared to the results of various radiative transfer calculations of the ground truth data to TOA radiance (look-up table). The best fitting atmosphere, characterized by an assumed urban aerosol model and a certain horizontal visibility is then chosen by minimization of the relative rms error.

3.2 Comparison of Ground Measurements to MERIS Observations

Figure 4 through Figure 8 show the results of the MODTRAN modelled top-of-atmosphere radiances from the spectral ground truth data, together with the MERIS measured radiances in the corresponding MERIS bands for the four data sets used for vicarious calibration of MERIS over land. Whereas Figure 5 shows the results from the sun photometer data inversion approach, the other figures are based on the findings of a best fit approach, in which an urban aerosol model is assumed as best representation of the untypical atmospheric conditions during data take. It is obvious that the shapes of the modelled curves and the MERIS measured TOA radiances do not fully match. Especially the first band at 412.5 nm (aerosol type sensitive), band 11 (oxygen at 760 nm) and band 15 (water vapour absorption region at 900 nm) are critical in the modelling. These bands need more precise atmospheric reference data (e.g., meteorological data) for vicarious calibration. Apart from these bands, the relative differences between MERIS measured and radiative-transfer modelled TOA radiances, as they are given in Table 3, do not exceed 6% (except for band 2 on October 21, 2002).
Figure 5 and Figure 6 both show the results for the August 22, 2002 situation. Sun photometer data inversion leads to an assumed atmosphere of 40 km visibility (urban model), whereas in the best fit approach (based on an urban model), a horizontal visibility of 90 km is found as having a minimum rms error. This shows the minor importance of the visibility parameter at high visibility conditions relative to the aerosol model. The mean differences between measured and modelled top-of-atmosphere radiances for the two approaches are almost identical (see Table 3).

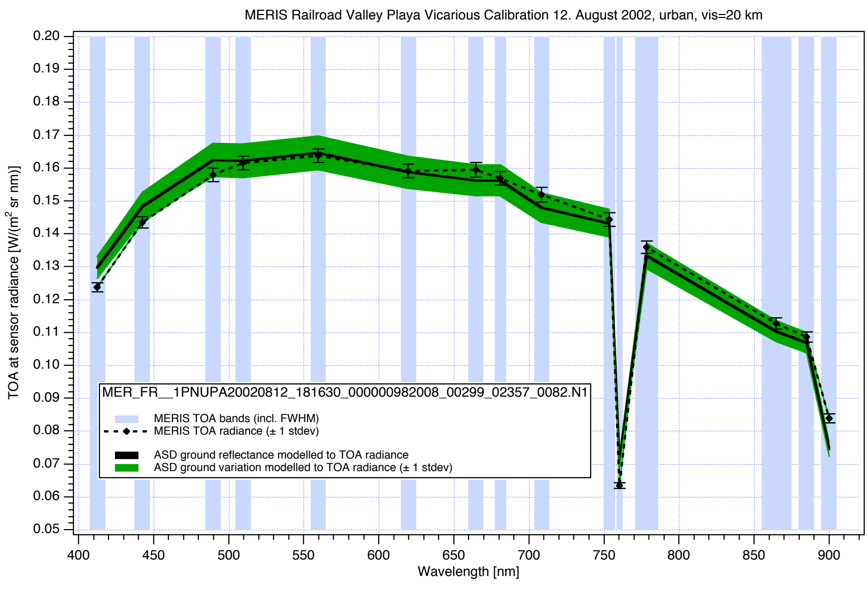

Figure 4: MERIS measured and MODTRAN modelled top-of-atmosphere radiance
for August 12, 2002 (best fit approach).

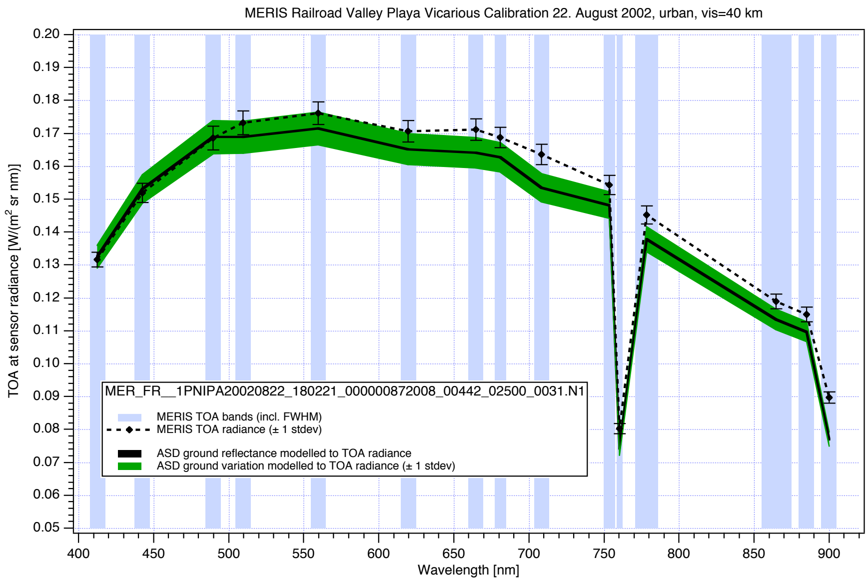

Figure 5: MERIS measured and MODTRAN modelled top-of-atmosphere radiance for August 22, 2002 (sun photometer data inversion approach).

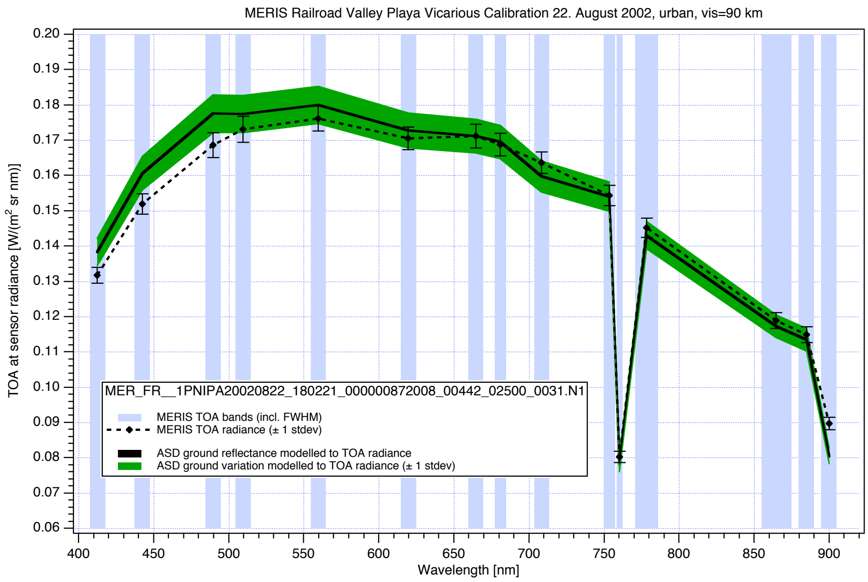

Figure 6: MERIS measured and MODTRAN modelled top-of-atmosphere radiance for August 22, 2002 (best fit approach).

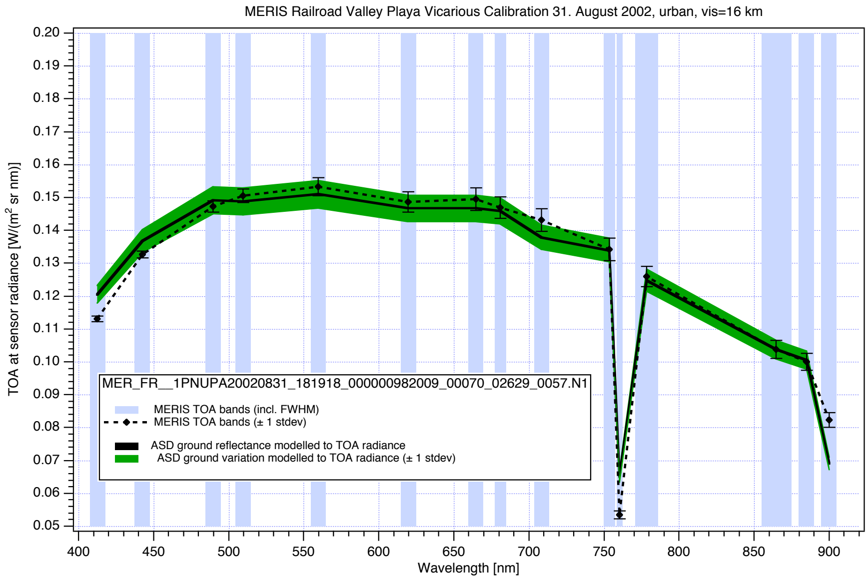

Figure 7: MERIS measured and MODTRAN modelled top-of-atmosphere radiance for August 31, 2002 (best fit approach).

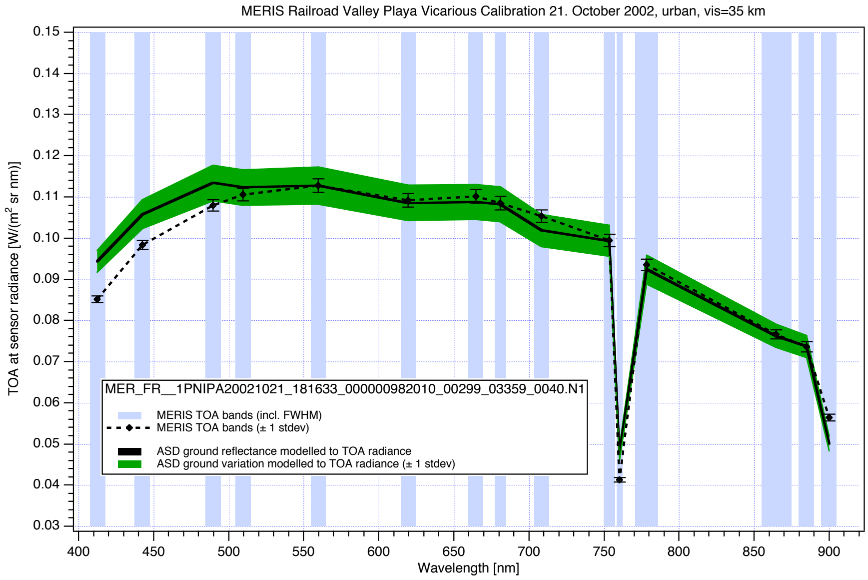

Figure 8: MERIS measured and MODTRAN modelled top-of-atmosphere radiance for October 21, 2002 (best fit approach).

In addition to the bandwise relative differences between MERIS measured and MODTRAN modelled TOA radiances, the mean relative rms errors between measured and modelled radiances for all four dates under investigation are given in Table 3. By excluding the before-mentioned bands 11 (760.35 nm) and 15 (899.86 nm), the relative rms error can be reduced substantially. The mean relative rms error represents the overall uncertainty of the vicarious calibration method, since all potential error sources account for the quality of the data fit. An error budget is given in Table 4. While the uncertainty in the knowledge of the solar irradiance, the spectralon reflectance, the relative surface BRF and the illumination geometry are well known for the testsite [5], the uncertainty of the atmospheric characterization is highly dependent on whether reliable sun photometer data is available or whether a best fitting, but poorly known atmosphere is fitted to the data sets. As a consequence, various uncertainties for atmospheric characterization are contained in Table 4. Surface reflectance errors including errors in geolocation, in-situ sampling, test site inhomogeneity and instrument absolute calibration are not included in this error budget, because they are assumed to be represented by the ±3% variability of the spectral measurements (±1 stdev from the mean), as indicated in Chapter 2.2.

MERIS channel	**Center Wavelength (nm)**	**Differences between MERIS and TOA radiances from VC (%)**				
		12. 8. 2002 urban vis=20 km	22. 8. 2002 urban vis=40 km	22. 8. 2002 urban vis=90 km	31. 8. 2002 urban vis=16 km	21. 10. 2002 urban vis=35 km
1	412.545	-4.879	-0.604	-4.994	-6.614	-10.879
2	442.401	-3.360	-0.844	-5.745	-3.141	-7.658
3	489.744	-2.890	-0.335	-5.314	-1.267	-5.069
4	509.700	-0.394	2.356	-2.498	1.147	-1.624
5	559.634	-0.469	2.543	-2.167	1.530	0.054
6	616.620	0.212	3.035	-1.278	1.325	0.634
7	664.640	1.994	4.028	0.040	1.805	1.317
8	680.902	0.359	3.442	-0.482	0.674	0.298
9	708.426	2.637	5.884	2.318	3.657	3.282
10	753.472	0.857	3.856	0.238	0.218	0.097
11	**760.354**	**-11.750**	**6.999**	**2.524**	**-21.662**	**-15.637**
12	778.498	1.949	5.011	1.520	0.941	1.195
13	864.833	2.098	4.512	1.336	-0.026	0.550
14	899.849	1.562	4.465	1.374	-0.436	-0-083
15	**899.860**	**11.086**	**13.230**	**10.370**	**16.217**	**11.107**
Mean difference (%) **Excl. channel 11 and 15**		3.100 **1.820**	2.685 **2.140**	2.813 **2.254**	4.044 **1.752**	3.966 **2.518**
Mean relative rms error (%) **Excl. channel 11 and 15**		4.690 **2.911**	5.943 **3.783**	4.019 **2.910**	7.146 **3.684**	5.953 **5.311**

Tab.3: MERIS and VC top-of-atmosphere radiances differences for the observed dates of MERIS data takes.

Error Source	**Absolute Uncertainty (%)**
Solar Irradiance Knowledge	2
Spectralon Reflectance Knowledge	1.5
Relative Surface BRF Knowledge	1
Atmospheric Characterization	< 2[1] < 7.15[2] < 4.58[3]
Cosine of Solar Zenith	< 0.1
Root-mean-square	**< 3.36[1]** **< 7.15[2]** **< 5.31[3]**

Tab.4: Vicarious calibration error budget.

[1] Using representative sun photometer data
[2] Based on maximum relative rms error of atmosphere fit including all channels (August 31, 2002 case)
[3] Based on maximum relative rms error of atmosphere fit without channels 11 and 15 (October 21, 2002 case)

CONCLUSIONS

Reflectance-based vicarious calibration methods generally have absolute uncertainties of 3-5% [8]. It is obvious from this study, that an accurate characterization of the atmosphere during a vicarious calibration experiment is crucial. The absolute uncertainty of this study's VC activities is estimated around 3.36%, given reliable sun photometer data is available. Under the absence of such data, the absolute uncertainty of the method exceeds 7%. Apart from band 1 (sensitive to aerosol type, 412.55 nm), band 11 (oxygen band at 760 nm), and band 15 (water vapour absorption region at 900 nm), all bandwise VC results lie within less than 6% of MERIS measured TOA radiances (except for band 2 on October 21, 2002). These bands need very precise atmospheric characterization for VC. The mean differences between MERIS- and VC- mean TOA radiances do not exceed 4.1% for any of the dates under investigation. Exclusion of band 11 and band 15 results in mean differences between 1.8-2.5% for all data sets. An incorrect assumption about aerosol absorption can strongly affect the VC accuracies of the shorter wavelengths bands. During summer 2002, North American wildfires strongly altered the type of atmosphere generally present at the test site. More stable atmospheric conditions over a certain regional extent and radiative transfer model inversion including non-standard aerosol models (e.g., the influence of black carbon particles) could further improve VC results.

From the results of this multitemporal VC experiment, no need to update the MERIS calibration is formulated. Although differences between measured and modelled TOA radiances greater than 6% occur in several bands, the uncertainties of the VC method and the accuracy requirements of MERIS absolute radiometric calibration (< 6%) do not allow to suggest a calibration update. Nevertheless, multitemporal VC, supported by extensive ground truth data collection, bears the potential to monitor the radiometric performance of a sensor over time. Surface HDRF measurements using a goniometer could improve the VC of large field-of-view sensors, since an off-nadir geometry could be modelled more precisely when using directional reflectance data other than from nadir. Spectrodirectional ground truth should be acquired as close to the time of the sensor overflight as possible, in order to minimize vicarious calibration errors due to temporal surface reflectance changes.

Based on the findings of this study, a VC experiment in a very large and spectrally homogeneous area (eg., Erg Murzuk (Libyan Sahara)) with stable atmospheric conditions is proposed. The supposed uniform test site should preferably fill the complete field-of-view of the five MERIS cameras, in order to satisfactorly address the individual camera behaviours and directional effects.

ACKNOWLEDGEMENTS

This project is supported by the Swiss Federal Office for Education and Science in the framework of CH-Intex (Nationaler Unterstützungskredit an internationale Experimente) and the University of Zürich. The on-site support of the Remote Sensing Group of the University of Arizona is greatly acknowledged.

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